COBRA-DDP: Trajectory Generation and Collision Avoidance Augmentations for eVTOL Vehicles

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Outline

- Emerging Aviation Landscape
- Intelligent Contingency Management
- Trajectory Generation
- COBRA-DDP (Previous Research)
- Bernstein Polynomials (BP)
- Optimal Reciprocal Collision Avoidance (ORCA)
- BP and ORCA
- BP and Differential Dynamic Programming (DDP)
- Model Predictive Control (MPC) Results
- Conclusions

Research Contribution: Model Predictive Control (MPC) formulation of combined BP, ORCA and DDP

Real-Time Collision Avoidance of Stationary/Moving Obstacles!

Emerging Aviation Landscape

- Novel aerospace sectors: missions and vehicles (e.g., autonomous cargo delivery)
- Business case for high levels of flight autonomy (e.g., no onboard pilot, 1-to-many humans to autonomous vehicle)
- Government/Industry/Academia are crafting new transportation system(s)
- New Paradigm: Anyone, Anywhere, Anytime
- Proliferation of Electrified Vertical Takeoff and Landing (eVTOL) vehicle configurations
- Highly non-linear, over-actuated, transition vehicles with very challenging aero-propulsive modeling
- Tight integration between flight control and trajectory planning
- New technologies: more likely to fail
- Narrow performance margins (e.g., battery life) with high safety levels required (e.g., urban flight)

Intelligent Contingency Management (ICM)

- Autonomous Flight for Nominal Operations: Exists today!
- Off-Nominal (i.e., Contingencies) Operations: Biggest Research Challenge!

History has shown priorities are:

1. Aviate (i.e., maintain control)
2. Navigate (i.e., trajectory planning)
3. Communicate

Humans Are Really Good ICM!

Cascading Systems Failure + Environment + Perception

- **Generator Failure on Cat Shot**
- **Cascades to Multiple Systems**
  - **No Visible Horizon…**

Human (ICM):

- **Aviate**
- **Navigate**

Autonomous (ICM):

Aviate:

- Robust & Adaptive Control
- Safety (Certificates) & Learning Control
- Failure ID & Flt Envelope Estimation
- Collision Avoidance & Pattern Entry
- Perception & Environment…
- ML training & off training guarantees

Navigate:

- Planners: Long, Short, Contingency (Spectrum)
- Perception & Environment
- Recognize Contingency /Failures and Replan…
- Multi-path and Optimizations…

Trajectory Generation

Plans require degrees of dynamic complexity/timescales along a continuum

(Less) <-- Dynamic Complexity --> (More)

Recommendations:
What should the vehicle do?

- "By the book"
- Design considerations
- Low fidelity, general cases, low computational cost

Capabilities:
What is the vehicle capable of?

- Optimal control
- Reachability sets
- High fidelity, highly specific, high computational cost

Autonomy Algorithms:

Seamlessly generate and utilize trajectories based on minimum level of dynamic complexity and fidelity modeling necessary for the task while facilitating communication with other autonomy algorithms with dissimilar dynamic complexity needs

Piecewise Bernstein Polynomial (BP) Curves:

Advantages: Fast and compact trajectory representation, smooth derivatives (position, velocity & acceleration)
Disadvantages: One piecewise segment cannot represent all curves exactly (e.g., circular arcs)

Optimal Reciprocal Collision Avoidance (ORCA):

Advantages: Fast computation for large number of cooperative/non-cooperative with separation assurances
Disadvantages: No assurance of dynamic feasibility

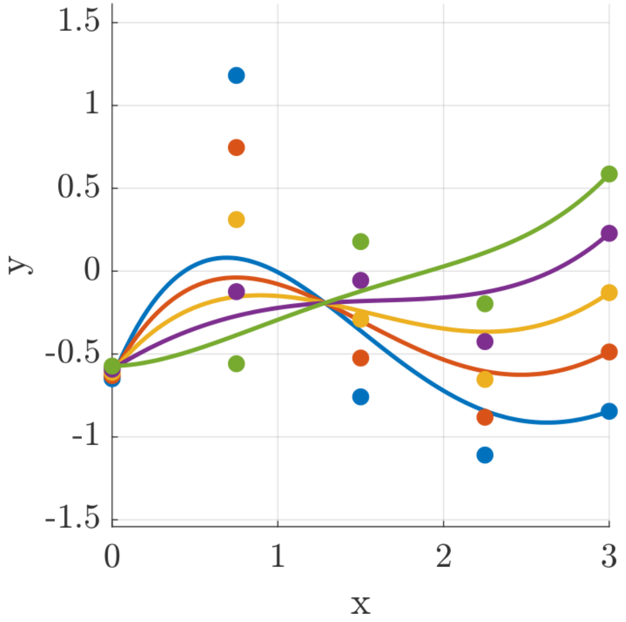
Differential Dynamic Programming (DDP):

Advantages: Fast computation of dynamically feasible optimal trajectories
Disadvantages: Degraded computation speed for incorporation of state constraints (e.g., obstacles)

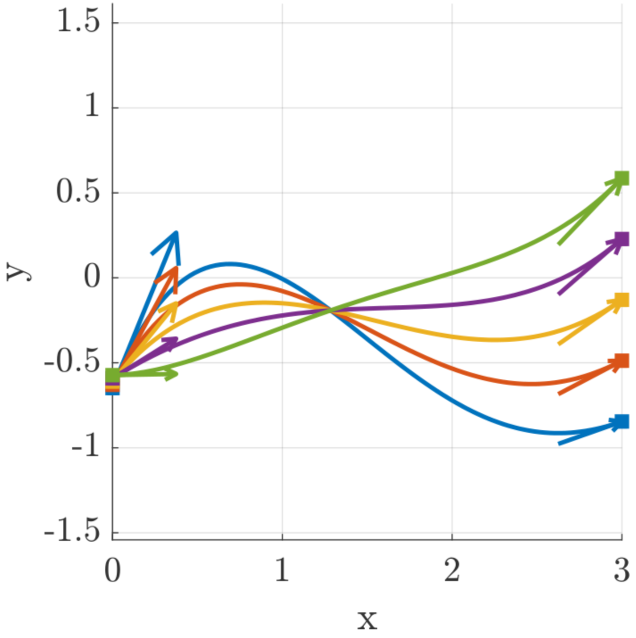
Previous Research: Not Real Time!

Bernstein Polynomials - Overview

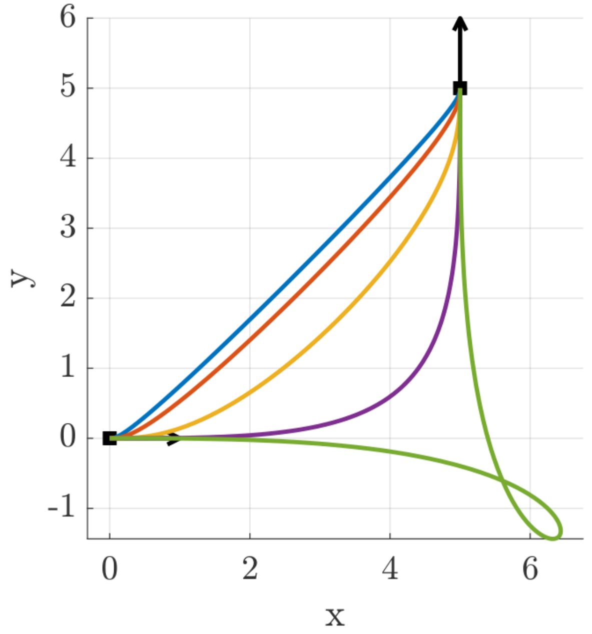
- Bernstein Polynomials have many mathematical properties that make them a good choice for trajectory planning
- Through a slight modification, they can be used to directly interface with other algorithms that have dynamic constraints on the endpoints, such as ORCA



Bernstein Polynomials are defined by parameters called control points



The derivative curve parameters can be computed in closed-form and used to meet dynamic constraints at end points

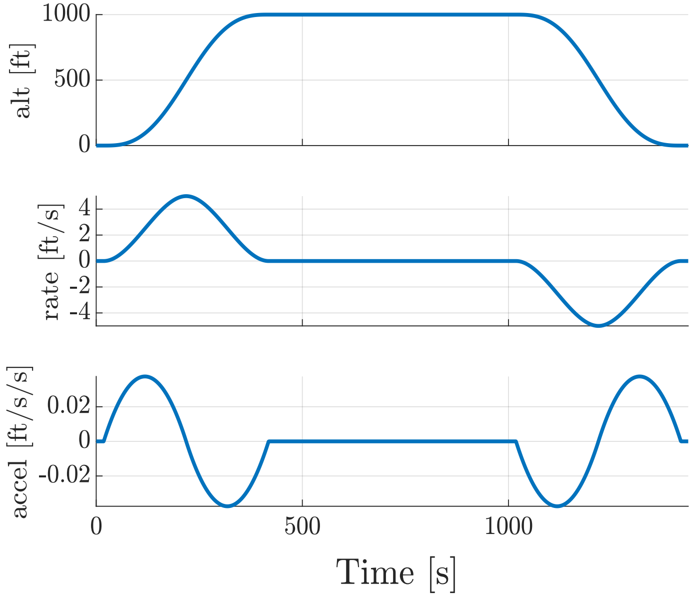


Fixing endpoints allows the curve to “tighten” or “extend” naturally for changing durations of the curve

Bernstein Polynomials – Dynamic Complexity

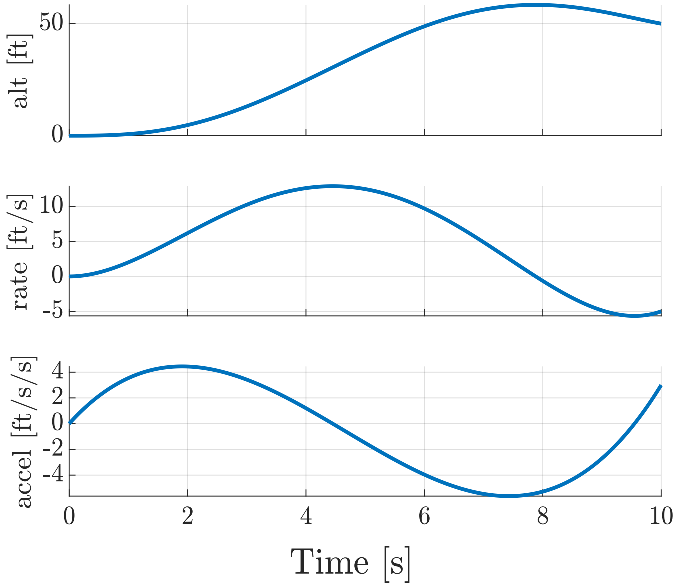
(Less) <--   Dynamic Complexity   --> (More)

Strategic – BP



Constructed from waypoints, with constraints added enforce typical behavior, e.g. position/velocity holds

Tactical – ORCA/BP



Fundamental component, can be used to construct arbitrary plans and used to inform state trajectories

Full State Dynamics – DDP

$$\dot{p} = \mathbf{v},$$
$$\dot{\eta} = S\omega,$$
$$\dot{\bar{\mathbf{v}}} = -\dot{\psi} e_3 \times \bar{\mathbf{v}} + g + m^{-1}\bar{F}\left(\bar{\mathbf{v}}, \omega, \bar{R}, u\right),$$
$$J\dot{\omega} = -\omega \times J\omega + \tau\left(\bar{\mathbf{v}}, \omega, \bar{R}, u\right),$$

Vehicle specific, waypoints define first equation fully. Additional waypoints may be needed to define orientation etc.

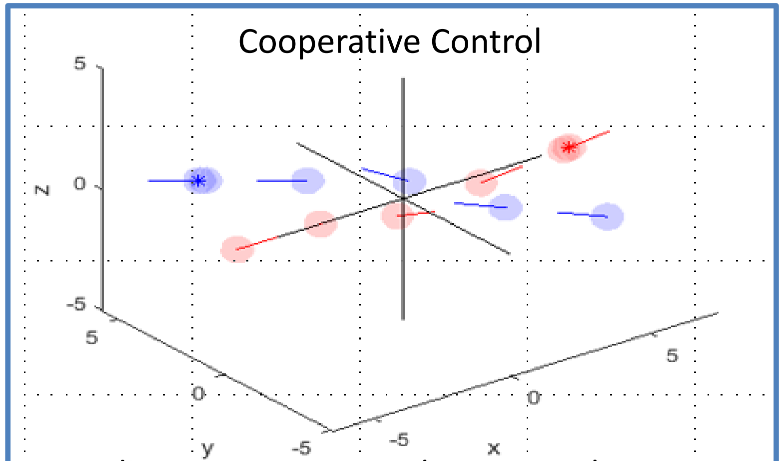
Optimal Reciprocal Collision Avoidance Algorithm (ORCA)

ORCA Algorithm (robotics community focused):

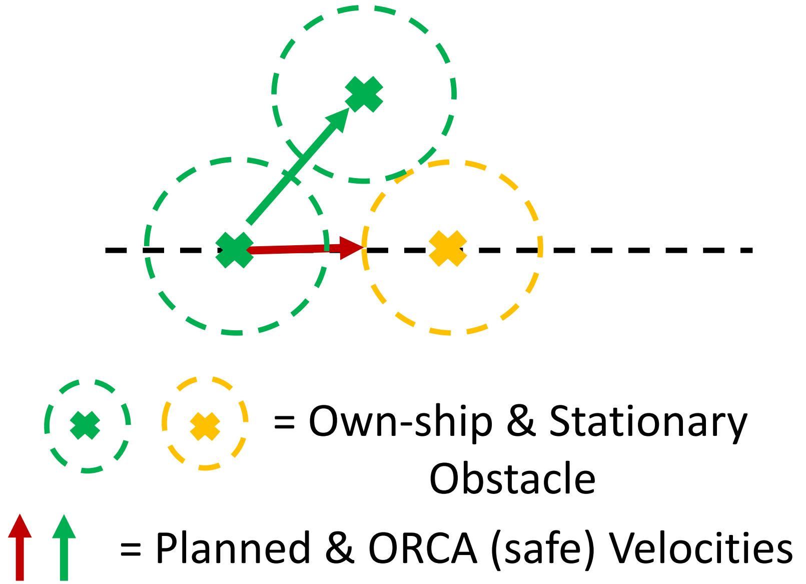
Collision Avoidance: robotics literature defines as autonomous robot navigation with fixed/moving obstacles (other intelligent vehicles)
Recurring cycle: sense/act, repeat

ORCA:

- Input: position and velocity knowledge (own-ship, obstacles/vehicles)
- Output: next own-ship velocity step (magnitude and direction)
- Point modeling (no vehicle dynamics) with safety sphere (keep-out radius)
- “Velocity object” representations, provides mathematical guarantees of collision free for lookahead time
- Cooperative law: each vehicles applies ½ velocity correction
- Uncooperative law: own-ship takes 100% of velocity correction

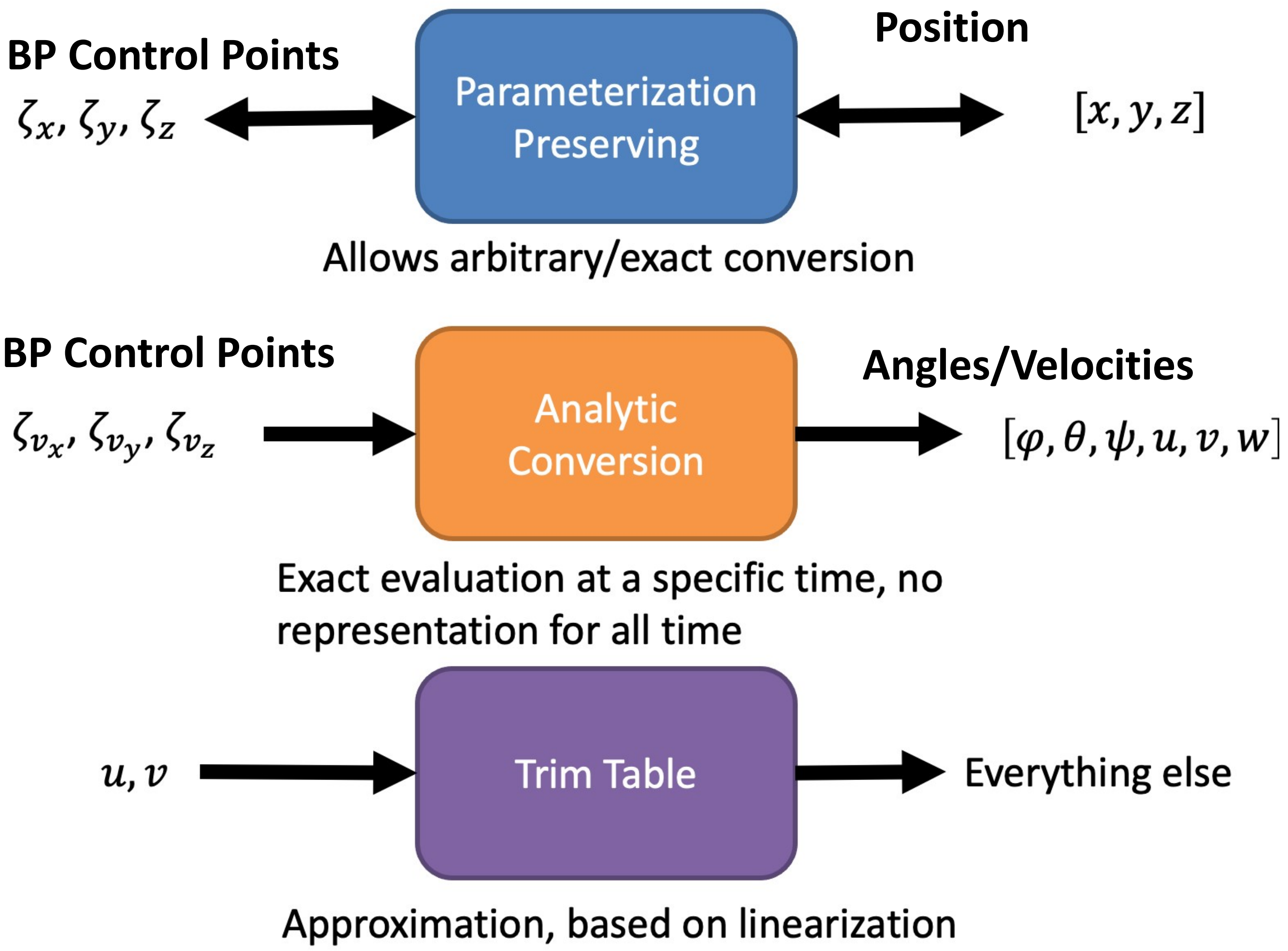


Credit: Bart Bacon, Langley Research Center



Continuous Trajectory Generation

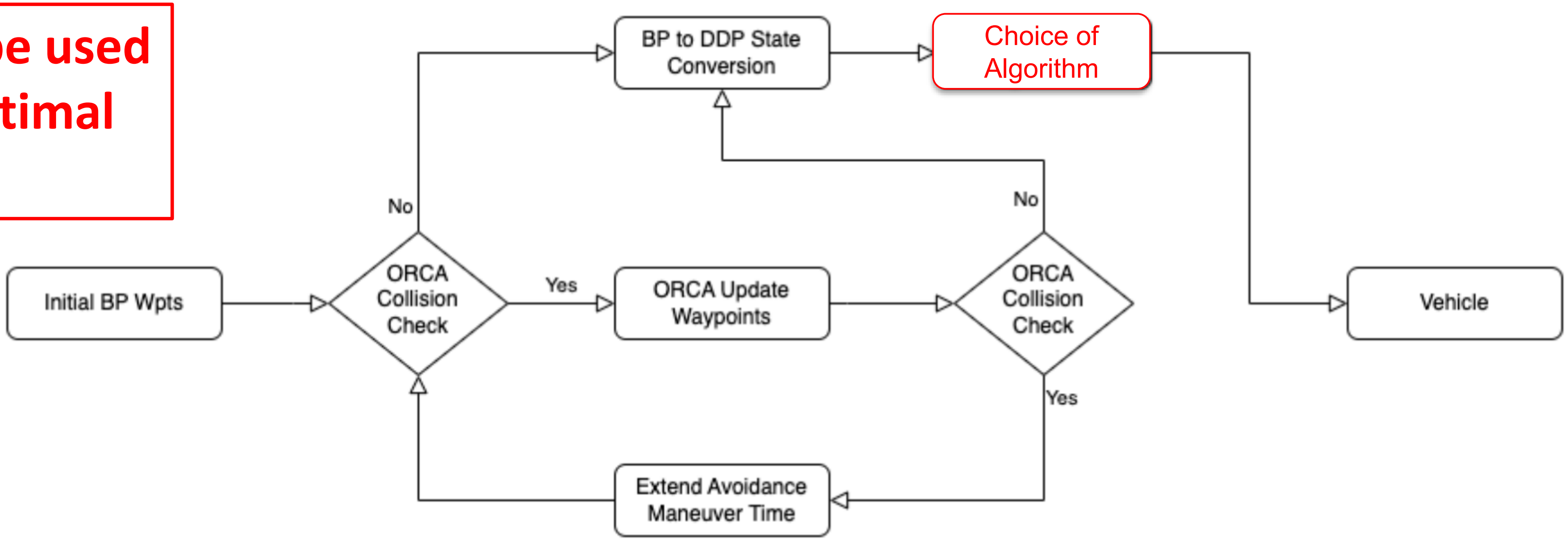
- BP waypoints are converted into states for DDP to optimize
- Linearized trim table of cruise are interpolated to complete trajectory states/controls
- These nonoptimal states and control serve as strong starting point for DDP optimization
- BP waypoints can be sampled efficiently at whatever rate DDP requires



BP and Differential Dynamic Programming (DDP)

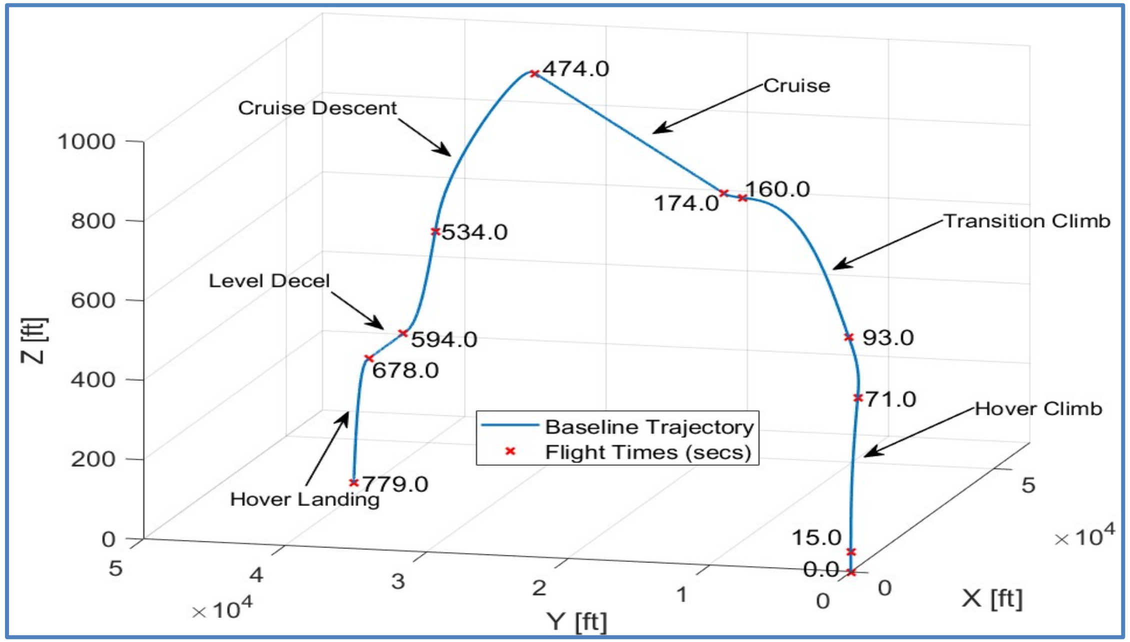
- Leverages ORCA fast collision avoidance checks and preferential avoidance direction selection
- BP's serve as compact trajectory representation between ORCA and DDP that can be quickly evaluated at any time along the curve
- DDP provides short time horizon dynamically feasible optimal trajectories given simplified trajectory

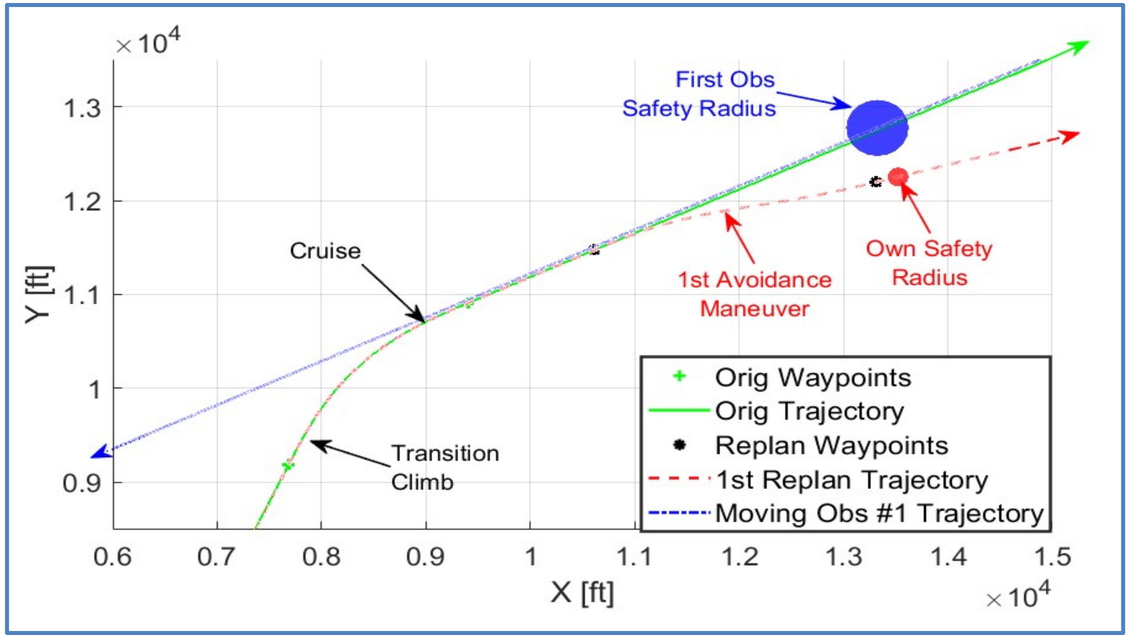
COBRA structure can be used with any iterative optimal control solver!



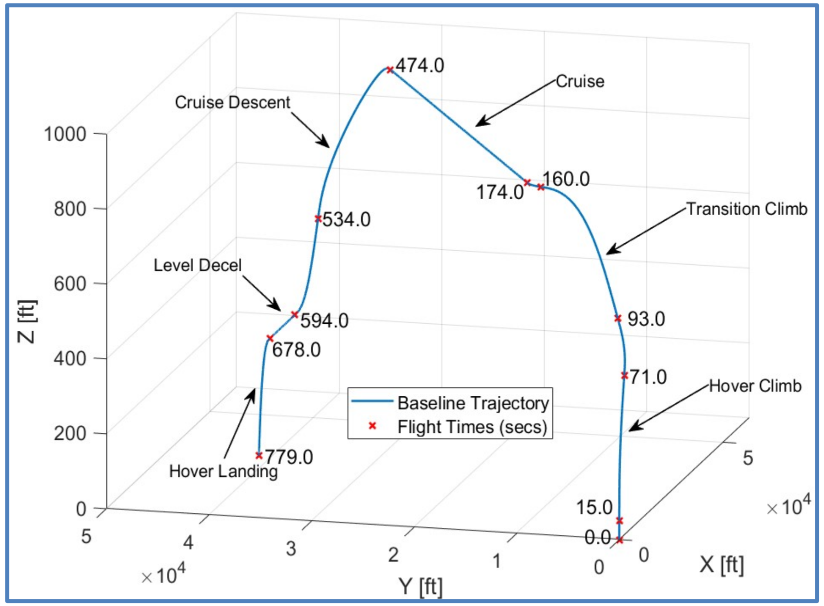
Experimental Result

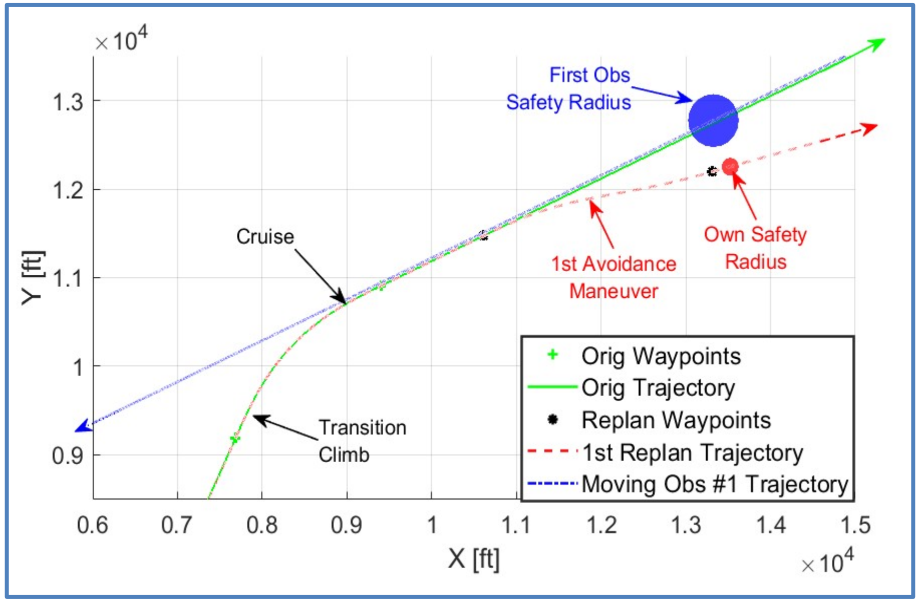
- Full flight tested
  - Vertical Takeoff/Landing
  - Transition
  - Cruise
- Replanning due to multiple moving obstacles
  - Avoidance of one obstacle requires planning to avoid the other
- Replanning descent portion due to large stationary obstacle
- BP-ORCA Time Horizon: 15 seconds
- DDP Time Horizon: 2 seconds

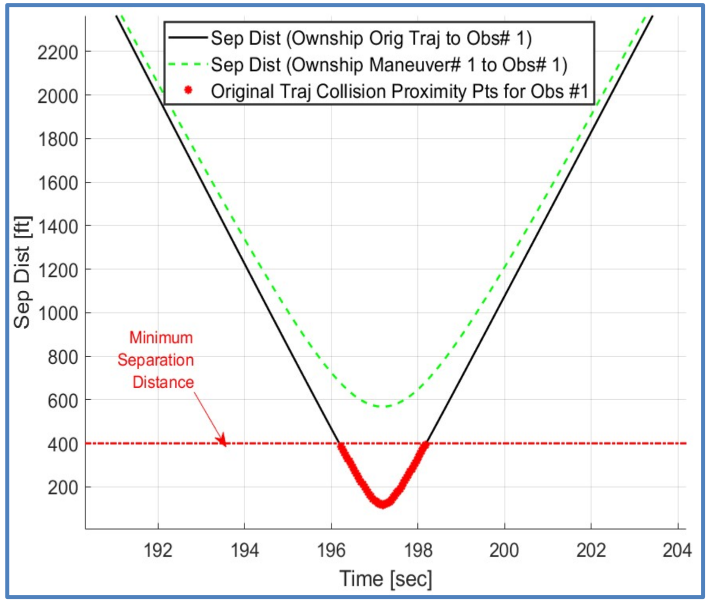


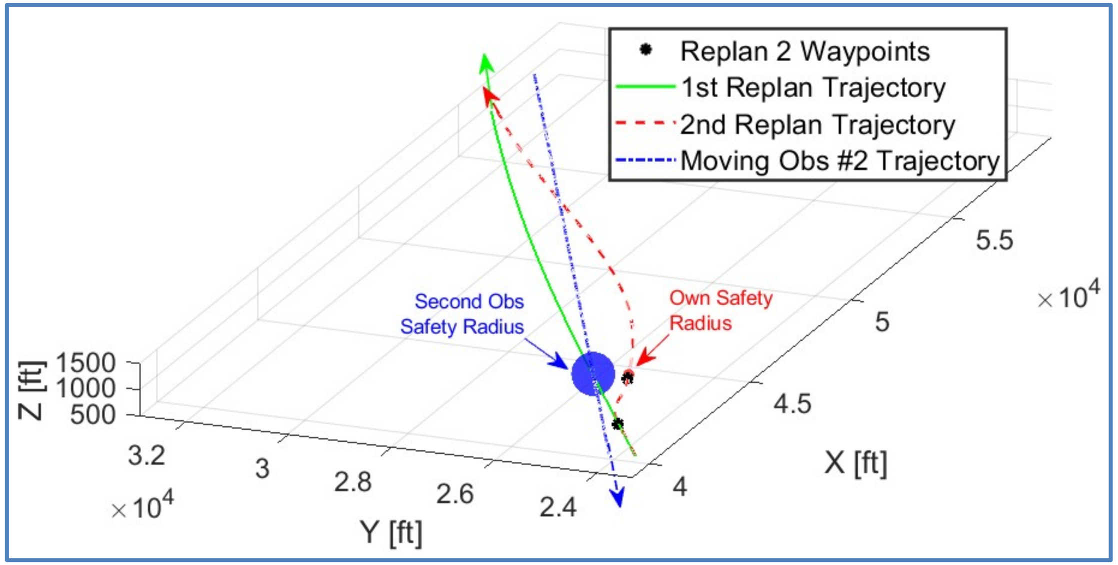


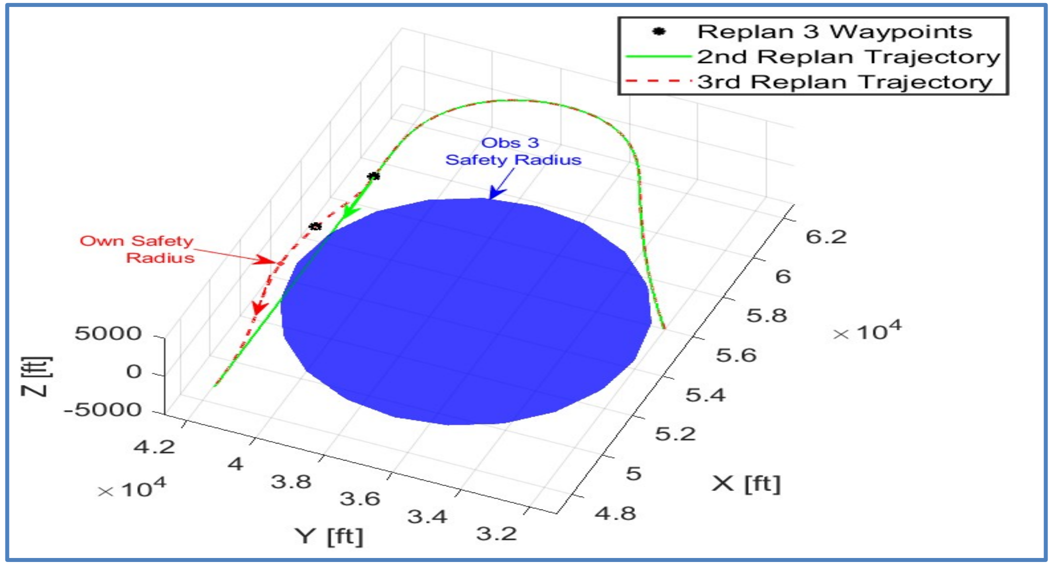
BP and Optimal Reciprocal Collision Avoidance (Continued)



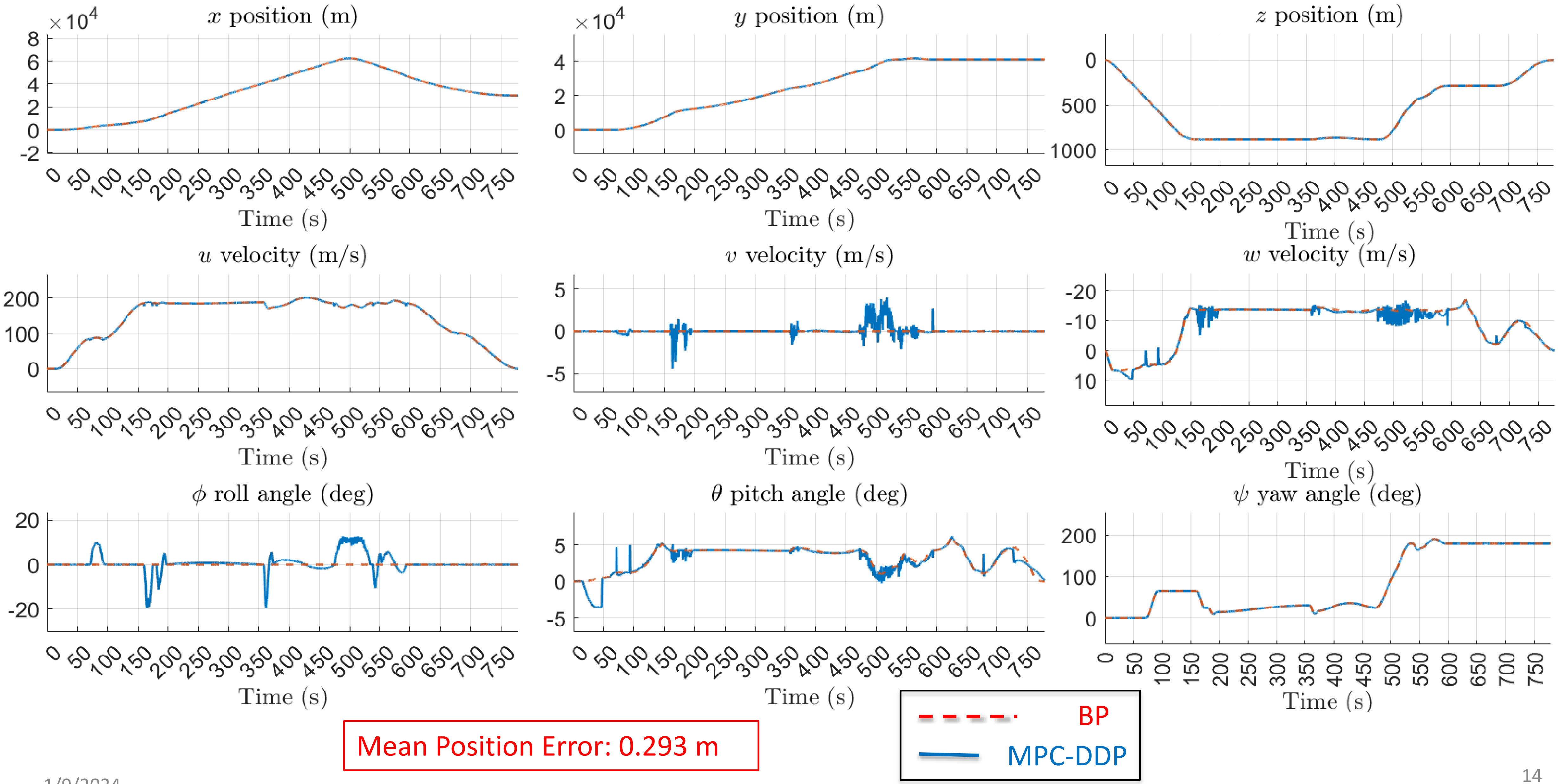








MPC COBRA Results



Mean Position Error: 0.293 m

Future Work

Conclusion

- Presented Receding horizon COBRA-DDP implementation
- Enables online planning and replanning
- Demonstrated in simulation for a UAM class vehicle

Extended demonstration

- Many obstacles
- Full mission execution
- Towards relevant environment (weather, traffic, urban obstacles, popup contingencies, etc.)

Algorithm

- Integrate mission management, higher level decision making. (Selecting between multiple good options, e.g., which way to go around an obstacle)
- Continuous propagation of multiple contingencies for precomputed alternate routes
- Structured integration of DDP/MPC with a baseline controller
- Tracking and approximation errors to help determine safety radius and maneuver start time needed to maintain safety radius

QUESTIONS ?

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